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13. ABSTRACT *(Maximum 200 words)*
This paper examines the fundamental differences between the parallel and serial methods for calculation of clothing insulation and demonstrates the differences in the insulation values calculated using these two methods. The parallel method is based on the assumption that manikin surface temperatures were uniform (UST) while the serial method is based on the assumption that manikin heat fluxes were uniform (UHF). Eleven clothing ensembles were evaluated on manikins in UST mode. Three of them were further evaluated on manikins in UHF mode. Insulation values were then calculated using both the serial and parallel methods. Results from UST mode showed that the parallel insulations ranged from 1.24 to 5.79 clo while the serial insulations ranged from 1.43 to 7.98 clo. Differences in the parallel and serial insulations increased as the insulation increased, and the serial insulations were approximately 14-38% higher than the parallel insulations. Results from UHF mode showed that the parallel insulations were 1.30 to 5.89 clo and close to the serial insulations of 0.34 to 5.99 clo. In conclusion, only the parallel method should be used when manikins are operated in UST mode and only the serial method should be used when manikins are operated in UHF mode.

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# DIFFERENCES IN CLOTHING INSULATION DETERMINED WITH THE PARALLEL AND SERIAL METHODS

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## INTRODUCTION

Clothing insulation can be measured on thermal manikins consisting of multiple, independently heated and regulated segments. The power supply to each segment ($Q_i$) and the temperatures of each segment ($T_i$) are measured to calculate the segmental value of clothing insulation ($I_i$). Total clothing insulation ($I_t$) is then calculated from the segmental values. There has been an on-going discussion over the use of parallel or serial methods to calculate $I_t$ (Nilsson 1997; Havenith 2005; Kuklane et al. 2005; Holmer 2006). From the perspective of heat transfer, the differences are apparent. The parallel method assumes a uniform skin temperature for the thermal manikin, whereas the serial method assumes a uniform heat flux. This paper will address the fundamental differences underlying the parallel and serial methods, and illustrate the differences in $I_t$ calculated using both methods.

## METHODS

*Analysis:* The selection of the method for calculating $I_t$ depends on the operating mode of the manikin. In most cases, manikins are operated in the uniform skin temperature (UST) mode. In a few cases, the manikins are operated in the uniform heat flux (UHF) mode. In the UST mode, $T_i$ are set to a constant and $Q_i$ are adjusted to maintain the selected constant $T_i$. By using a uniform temperature, heat transfer among segments is minimized, and $Q_i$ equals the heat loss from the segment to the environment. Thus $I_i$ can be calculated by:

$$I_i = \frac{T_i - T_a}{Q_i} A_i \quad (1)$$

*where* $T_a$ is the air temperature and $A_i$ is the segmental area.

As the total heat loss (Q) is the sum of segmental heat losses, a formula using $I_i$ to calculate $I_t$ can be derived using Eq. 2, which describes the parallel method for calculating $I_t$.

$$I_t = \frac{A}{\sum \frac{A_i}{I_i}} \quad (2)$$

*where* A is the total surface area.

In UHF mode, $Q_i/A_i$ is set to constant and equal to Q/A. Thus $I_t$ can be calculated using Eq. 4, which is derived from Eq. 3, and describes the serial method for calculating $I_t$.

$$I_t = \frac{\sum \frac{A_i}{A} T_i - T_a}{Q} A \quad (3)$$

$$I_t = \sum \frac{A_i}{A} I_i \quad (4)$$

However, the derivation of Eq. 4 from Eq. 3 contains a systematic error. When the heat fluxes are held uniform, the skin temperatures are often not uniform. The temperature differences cause heat transfers from high to low temperature segments. In other words, $Q_i$ is often not equal to the heat loss from the segment to the environment, and $I_i$ can not be calculated by Eq. 1. Thus, Eq. 3, rather than Eq. 4, should be used to calculate $I_t$.

*Measurement:* Fifteen clothing ensembles, with insulation that was evenly or unevenly distributed, were evaluated on two manikins at our Institute, to demonstrate the differences that occur when the parallel or serial methods are used to calculate $I_t$. Control set-points $T_i$ and $T_a$ were 33°C and 30°C for 10 ensembles, and 35°C and 20°C for 5 ensembles (ASTM test conditions). Each ensemble was tested three times to ensure the accuracy of measurements.
One manikin had 18 independently heated thermal zones plus an additional heated guard zone at the neck mounting plate, and the other one had 14 independently heated thermal zones. The zones were wet zones with an integrated sweat dispenser. The manikins were covered with a cotton skin layer to evenly distribute water over the zone surface.

## RESULTS AND DISCUSSION

The parallel $I_t$ and serial $I_t$ of the 15 ensembles were shown in the Figure 1. The

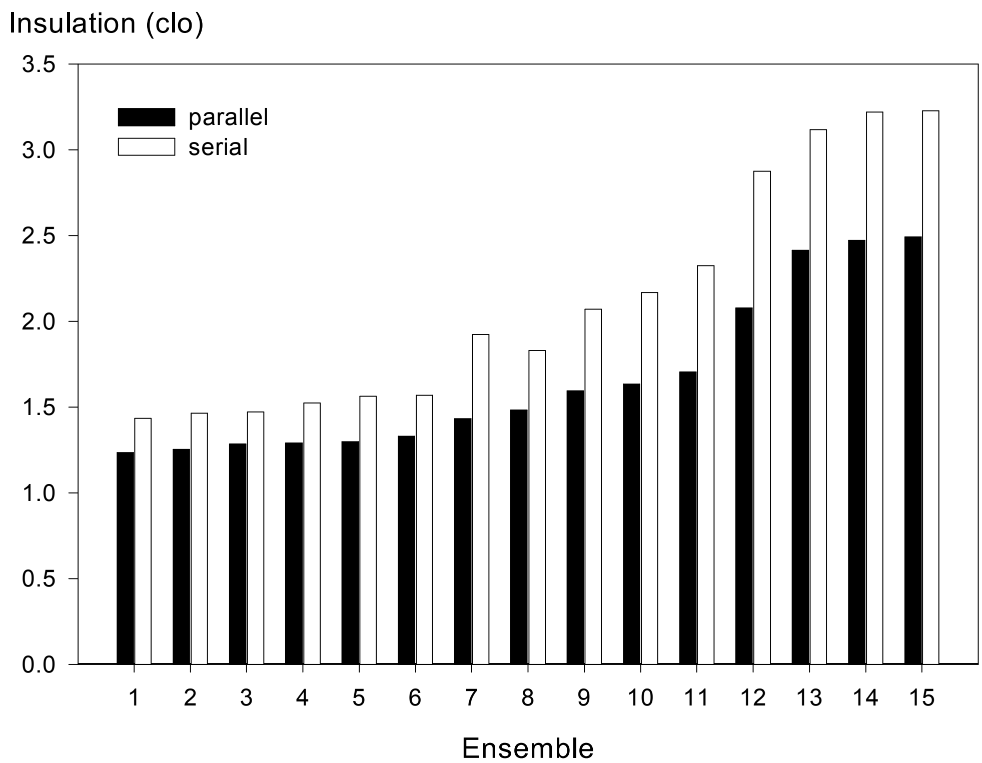


**Figure 1.** Insulation of 15 ensembles, determined using the serial and parallel methods.

parallel $I_t$ values ranged from 1.24 clo to 2.49 clo, while the serial $I_t$ values ranged from 1.43 clo to 3.23 clo. Differences in the parallel $I_t$ and serial $I_t$ increased as $I_t$ increased. Values for the serial $I_t$ were approximately 14-38% higher than the parallel $I_t$.

These results indicate that the $I_t$ values calculated using the serial method are higher than results derived using the parallel method, this was consistent with previous observations (Nilsson 1997; McCullough et al. 2002). As a result, if the serial $I_t$ is used for whole-body heat balance analysis, the predicted heat loss would be underestimated by approximately 13-27%. A previous study observed that the human subjects were not able to achieve and maintain heat balance in cold environments when the serial $I_t$ was used to select clothing insulation (Kuklane et al. 2005), as the serial $I_t$ was higher and did not represent the true insulation the clothing provided. It was also observed in this study that the serial $I_t$ is sensitive to $I_i$ and becomes unrealistic when measurement from any segments are inappropriate due to high local insulation and very low power supply. This was consistent with observations in the inter-laboratory study of manikins used to measure thermal and evaporative resistance (McCullough et al. 2002).

Methods for the calculation of clothing insulation depend on the operating mode of the manikins. Only the parallel method should be used to calculate clothing insulation using insulation values from the individual segments when manikins are operated in UST mode. The serial method should be used when manikins are operated in UHF mode. Ideally, in UHF mode, skin temperatures should be uniform to minimize heat transfer among segments, and in that case, the parallel method is a viable option. The serial $I_t$ in UST mode does not yield total insulation that accurately represents the insulation performance of the clothing, and the resulting apparent insulation values will be misleading.

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